SEASONAL CHANGES IN TITAN'S METEOROLOGY BRING RAIN TO LOW LATITUDES. E.P. Turtle[1], J.E. Perry[2], A.G. Hayes[3], R.D. Lorenz[1], J.W. Barnes[4], A.S. McEwen[2], R.A. West[5], A.D. Del Genio[6], J.M. Barbara[6], J.I. Lunine[7], E.L. Schaller[2], T.L. Ray[5], R.M.C. Lopes[5], E.R. Stofan[8], [1]JHU/APL, Laurel, MD (Elizabeth.Turtle@jhuapl.edu), [2]Univ. Arizona, Tucson, AZ, [3]Caltech, Pasadena, CA, [4]Univ. Idaho, Moscow, ID, [5]JPL, Pasadena, CA, [6]NASA GISS, New York, NY, [7]INAF, Rome, Italy, [8]Proxemy Research, Rectortown, VA.

Introduction: The *Cassini* Imaging Science Subsystem (ISS) has observed Titan for ~1/4 Titan year, documenting changes in weather patterns and accompanying surface changes from late southern summer to early southern autumn [1]. Recent observations have shown extensive cloud systems at low latitudes (Fig. 1), suggesting seasonal shifts in Titan's tropospheric methane clouds. The observed cloud distributions and behavior suggest that Titan's general circulation is influenced by both the rapid temperature response of a low-thermal-inertia surface and the much longer radiative timescale of Titan's thick troposphere [1].

Intriguingly, the large low-latitude clouds observed in Sept.-Oct. 2010 were quickly followed by extensive changes on the surface (Fig. 2). Although there is evidence that liquids have flowed on Titan's surface at the equator in the past, to date liquids have only been observed on the surface at polar latitudes [2]. Moreover, the vast expanses of dunes in Titan's equatorial regions [3] require a predominantly arid climate, prompting the question of how often it rains at low latitudes. The rapid changes observed after the Sept. 2010 cloud outburst appear to be direct evidence of widespread methane rainfall reaching Titan's surface at low latitudes.

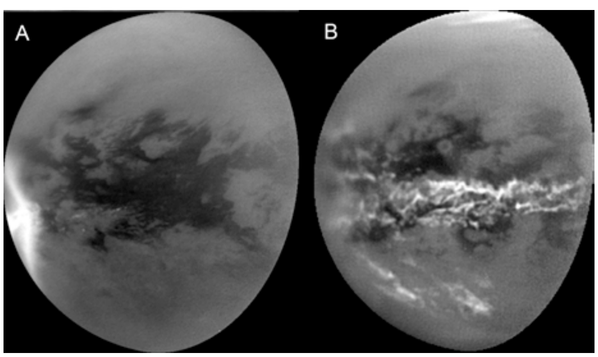

Figure 1: (A) Near-equatorial arrow-shaped cloud, 27 Sept. 2010. (B) Clouds at equatorial, mid-southern and high-northern latitudes, 18 Oct. 2010. Bright features are tropospheric methane clouds; shades of grey are surface features.

Cloud Observations and Implications: In 2004, Titan's late southern summer, extensive cloud systems exhibiting behavior consistent with convection were common in the south-polar region. Such activity decreased significantly after a large outburst in Oct. 2004 [1, 4]. In contrast, at mid-southern-latitudes, elongated streaks and small (~10 km) isolated clouds have appeared consistently. ISS first observed clouds at high northern latitudes in early 2007; they became common after Jan. 2008 [1]. We anticipate that convective cloud systems will develop at high northern latitudes by late northern summer. Only two small clouds have been observed at mid-northern latitudes, although these clouds may also become more common as northern spring progresses. Most recently, large cloud systems have been observed at low latitudes (Fig. 1). The appearance of extensive near-equatorial clouds is reminiscent of an earthlike Intertropical Convergence Zone (ITCZ); however, there are still too few observations to determine whether the clouds are part of a seasonal migration of the ITCZ or a short-lived event.

The ISS observations reveal strong latitudinal preferences and evidence of seasonal changes in Titan's general circulation [1]. Although longitudinal preferences are not evident, at high northern latitudes clouds are often seen near lakes and seas, consistent with availability of methane facilitating cloud formation. Comparing the observations to models of atmospheric circulation [5-11] demonstrates that (1) moist convective processes are essential to reproducing the observed atmospheric behavior and (2) the tropospheric dynamics may reflect a combination of a long-term response by the high-thermal-inertia atmosphere and more rapid forcing by temperature variations of the surface [1]. The tendency for clouds to appear at fixed latitudes suggests that the dynamics of the troposphere, whose radiative timescale greatly exceeds a Titan year, may include a component that responds sluggishly to its internal dynamics in addition to one that responds more quickly to surface forcing. On Earth, the ITCZ shifts abruptly from the winter to the summer hemisphere due to the oceans' large thermal inertia and to non-linear meridional advection of angular momentum by the mean circulation [12]. If momentum advection in a super-rotating atmosphere combined with a large atmospheric thermal inertia play a similar role on Titan, then our first observation of northern mid-latitude clouds in late 2009 may be a harbinger of a "sudden" shift of the ITCZ into the more illuminated northern hemisphere and the southern mid-latitude clouds, which have lasted longer than in Titan circulation models [9-11], will disappear in the next few years.

Surface Changes and Interpretation: ISS observations in Oct. 2010 (Fig. 2) of a region east of the Sept. 2010 cloud outburst revealed differences in surface brightness along the southern boundary of Titan's largest dune field, Belet [13]. Some terrain darkened by >10%, while adjacent areas remained unchanged (Fig. 2D, H). We can rule out observational effects and clouds [13], so the differences represent changes on Titan's surface. Although clouds obscured some areas on 14 Oct., changes had occurred by that time (Fig. 2B, F). However, only some of the darkened area persisted through 29 Oct. (Fig. 2C, G); other areas had brightened again, indicating the changes were short-lived in some places. The measured extent of changes that persisted until 29 Oct. is ≥500,000 km^2, extending ~2000 km east-west and >130 km across (Fig. 2).

Titan's dark regions consist of hydrocarbons, and brighter material is thought to be bright aerosols [14-15]. Although *Cassini* synthetic aperture radar (SAR) and Visual and Infrared Mapping Spectrometer (VIMS) data confirm the presence of dunes nearby, the changes do not appear to be the result of aeolian processes. Cryovolcanism is also an unlikely explanation.

Methane precipitation could affect a large area over a short period of time; the cloud observed on 27 Sept. was several hundred km in extent (Fig. 2A). Flooding and/or surface wetting could change the optical properties of the surface rendering it darker. In a narrow strip of SAR topography that crosses part of this region, areas of change do not correlate with low-lying areas, nor are there any obvious correlations between the new boundaries and pre-existing features in ISS, VIMS or SAR data [13]. Furthermore, flooding would require standing liquid over an area several times that of Ligeia Mare, Titan's second largest sea. These issues are resolved if, at least in some areas, darkening is due to surface wetting: much less precipitation is necessary, and the observed pattern results from variations in precipitation and the nature of the surface. Wetting of fine dark aerosol particles could be part of the unknown process by which such material is cemented together to form particles large enough to undergo saltation, required for dune formation [3]. Precipitation can also explain the brightening observed later in some places as different areas drain or dry at different rates.

Rainfall on Titan's arid equatorial surface, following the equinox (Aug. 2009), is consistent with atmospheric model predictions [10]. Even infrequent storms can form the observed channels [16-17], and, although the dune fields demonstrate that these latitudes are predominantly dry, they do not preclude occasional precipitation. Indeed, the geomorphology of terrestrial drylands is often dominated by fluvial features.

The frequency of such storms at low latitudes and the duration of this weather pattern during the equinox transition have important implications for Titan's methane cycle, atmospheric circulation, and rates of geologic modification.

References: [1] Turtle et al., *GRL*, in press. [2] Lopes et al., *Icarus 205*, 2010. [3] Lorenz et al., *Science 312*, 2006. [4] Schaller et al., *Icarus 184*, 2006. [5] Hourdin et al., *Icarus 117*, 1995. [6] Mitchell et al., *Proc. NAS 103*, 2006. [7] Tokano, *PSS 55*, 2007. [8] Richardson et al., *JGR 112*, 2007. [9] Rannou et al., *Science 311*, 2006. [10] Mitchell, *JGR 113*, 2008. [11] Mitchell et al., *Icarus 203*, 2009. [12] Xian and Miller, *J. Atm. Sci. 65*, 2008. [13] Turtle et al., *Science*, in review. [14] Clark et al., *JGR 115*, 2010. [15] Soderblom et al., *PSS 55*, 2007. [16] Jaumann et al., *Icarus 197*, 2008. [17] Collins et al., *GRL 32*, 2005.

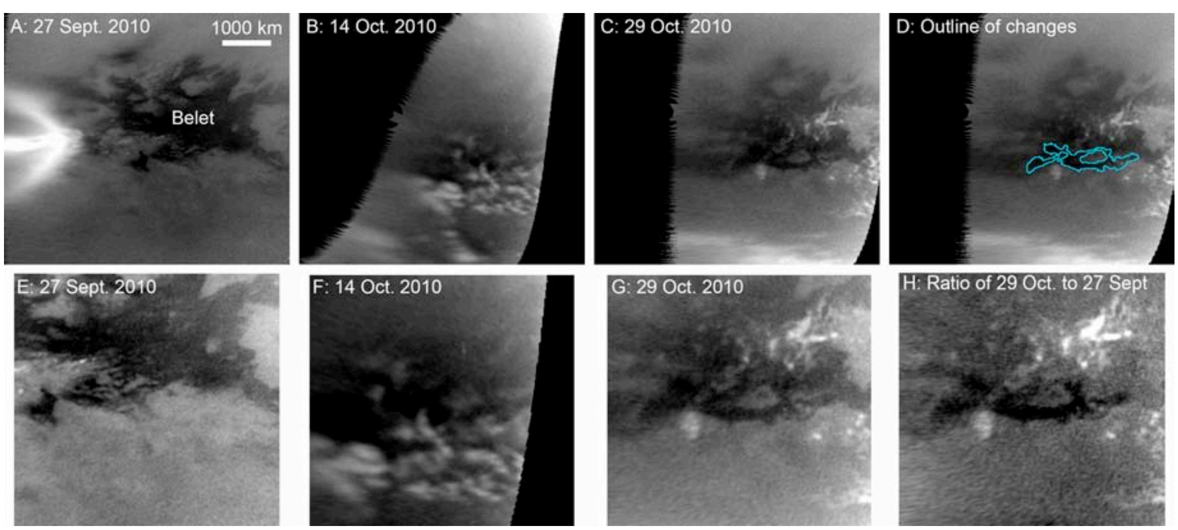

Figure 2: Recent ISS observations of clouds and surface changes (bright features are clouds; shades of grey are surface features). (A) 27 Sept., (B) 14 Oct., and (C, D) 29 Oct. 2010; area of surface change is outlined in (D). (E-G) are closer views of (A-C), and (H) shows the ratio of the image from 29 Oct. 2010 (G) to one acquired at a similar phase angle on 27 Nov. 2009. Variations in contrast toward the tops of some images (notably B and C) are due to higher emission angles. North is up in all images.